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DESIGN AND PREPARATION OF QUARTER-WAVE PLATE COATINGS

/91*

Gu Peifu Tangjinfa

ABSTRACT During non-normal incidence on multilayer reflectors, two polarization components will produce different phase shifts. Because of this, it is possible to use computer optimization to design film systems associated with specific phase differences. The object of this article is to design 90° phase films. Their functioning will then approximate quarter wave plates. Compared to traditional wave plates, their special features are that it is possible to use them for any wavelength, and they possess high phase difference precisions and large apertures. Two types of design methods are presented in the article. In conjunction with this, preparation techniques and experimental results are reported.

II. FORWARD

Traditional wave plates are formed by the use of double refraction characteristics associated with crystals. By comparison, thin film wave plates possess greater flexibility. Thin film wave plates are capable of use with ultraviolet, visible light, and even into infrared wave length ranges. They can be used in, for example, 10.6 μ high power lasers. This is something that crystal wave plates cannot handle. Secondly, thin film wave plate aperture dimensions can be made very large.

It is for precisely these types of reasons that, in recent years, thin film wave plates have given rise to serious attention among people. Zagloul, et al, [1] reported on design cases plating SiO_2 on silicon surfaces and Kawabata, et al [2], on plating MgF_2 on Ag, Al, and Cu. However, the reflection efficiency differences associated with two polarization components for these designs were usually relatively large. For

* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

this reason, Southwell [3] used computer optimization on multilayer designs associated with 90° phase differences to use at 10.6 μ. Then, Apfel [4] made use of graphics techniques in order to design methods supplying direct audio-visual perception. In conjunction with this, design cases were supplied associated with 22.5° and 0° phase differences. We used simple calculation methods and statistical experimentation methods, respectively, to design phase delay films used at 630nm (simply called phase films). This article will stress discussions on the design and preparation of phase films with very high reflection efficiencies and approximately equivalent $(R_p \approx R_s > 0.9)$ with phases equal to 90° $(\Delta = |\delta_p - \delta_s| \approx 90^\circ)$. Functions of this type of phase film are analogous to reflection type quarter wave plates. They are capable of causing linear polarized light to change into circular polarized light or vice versa. Of course, this type of design method is appropriate for use with any delay angle phase film.

II. FILM SYSTEM DESIGN

Thin film wave plates, in reality, are a special type of reflector. During non-normal utilization of reflectors, the two polarization components generally possess different amplitudes and phases. Our objective is--with a presupposition of given wave lengths (λ = 6328 A) and incident angles (45°)--to solve for film system designs which satisfy $R_p \approx R_s > 0.9$ and $\Delta = |\delta_p - \delta_s| \approx 90^\circ$. The simplest 90° phase films are nothing else than single /92
layer metal films. Their reflection amplitudes and phase changes are functions of metallic film optical constants and angles of incidence. Preparation of this type of metallic phase film is unusually convenient. Its drawback is relatively large differences in reflection efficiencies R_p and R_s. Moreover, it is only possible to satisfy 90° phase differences when quasi-Proust (phonetic) angles approximate incidence. For example, Al

reflector quasi-Proust angles are approximately 81°. At this time, $R_p \approx 0.71$, and $R_s \approx 0.98$. Assuming utilization angles require 45°, then, the phase difference which it is possible to supply is only approximately 13°.

As far as having to obtain high reflection efficiency 90° phase films is concerned, using media multilayer films is very difficult. It is not possible, simultaneously, to satisfy the two requirements of reflection efficiency and phase difference. Because of this, it is necessary to opt for the use of multilayer media film composite systems on metallic films.

Now, we first take a look at a situation in which a single layer transparent film is added onto a high reflection composite base (Fig.1). High reflection composite bases are capable of being metal films or, more commonly, multilayer media film systems on metallic films. Composite base complex amplitude reflection systems are:

$$\tilde{\gamma}_B = \gamma_B e^{i\delta_B}$$

In the equation, γ_B and δ_B are respectively the amplitude and phase shift associated with $\tilde{\gamma}_B$. With regard to the two polarization components, so long as we respectively mark the subscripts p and s, that will do.

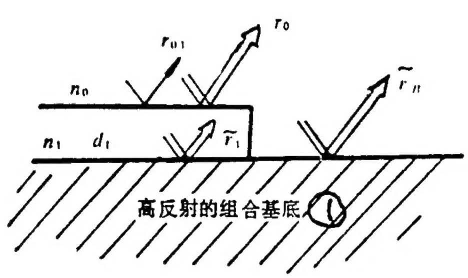


Fig.1 Symbol Conventions
Key: (1) High Reflection Composite Base

Due to phase thickness associated with transparent film (n_1, d_1) being

$$\phi_1 = \frac{2\pi}{\lambda_0} n_1 d_1 \cos\theta_1$$

θ: is the refraction angle in the transparent film in question. Because of this, the whole composite complex amplitude reflection system is

$$\tilde{\gamma}_0 = \gamma_0 e^{i\delta_0} = \frac{\gamma_{01} + \tilde{\gamma}_1 e^{-i2\phi_1}}{1 + \gamma_{01}\tilde{\gamma}_1 e^{-2i\phi_1}}$$

In the equation, $\gamma_{01} = \frac{n_0 - n_1}{n_0 + n_1}$

Considering very high composite base reflection efficiencies, when transparent films are added to their surfaces, reflection amplitudes follow film thickness changes and are very small. As a result, the equation above can be simplified to be

$$\tilde{\gamma}_0 = e^{i\delta_0} = \frac{\gamma_{01} + e^{i(\delta_1 - 2\phi_1)}}{1 + \gamma_{01} e^{i(\delta_1 - 2\phi_1)}} \qquad (1)$$

Solving for equation (1) δ_0 , it is finally possible to arrive at

$$\left.\begin{aligned} \operatorname{tg}\frac{1}{2}\delta_0 &= \frac{n_1}{n_0}\operatorname{tg}\left(\frac{1}{2}\delta_1 - \phi_1\right) \\ \Delta &= |\delta_{0p} - \delta_{0s}| \end{aligned}\right\} \qquad (2)$$

From equation (2), it can be seen that phase difference Δ is determined by transparent film refraction index n_1 and thickness d_1 as well as composite base phase shift $\delta 1$. So long as composite bases possess adequate phase shifts, as far as specified film layer refraction indices are concerned, it is possible, going through film thickness adjustments, to satisfy phase difference requirements. This means that it is only necessary to calculate reflection phase differences following changes in the outermost layer transparent film thicknesses as they change the status. In this way, design processes are then summarized as being one dimensional search processes for outermost layer thicknesses. Table 1 presents a number of design cases.

From Table 1, it is easy to see that composites associated with the majority of forms are all film system structures which can be expected to find 90° phase differences. Metallic membranes in film systems are capable of selecting for use Ag or Al. However, Ag reflection efficiencies--in particular, R_p--will be much higher than Al. Adjacent metallic layer media films are capable of using low refraction index membranes. They are also capable of using high refraction index membranes. However, low refraction index layers have higher reflection efficiencies. Moreover, it is easier to satisfy phase difference conditions. What should be pointed out is that 90° phase differences certainly do not appear in central wave length areas associated with 1/4 wave accumulation. They are normally on the two sides of 1/4 wave accumulation cut off zones. Therefore, it is possible to expect to opt for the use of specified wave lengths associated with the two sides of cut off zones to act as control wave lengths--just in the way shown in Table 1 for film systems 4 and 5. /93

TABLE 1. FILM SYSTEM EXAMPLES ASSOCIATED WITH λ=632 nm PRODUCING 90° PHASE DIFFERENCES

(1) 序号	(2) 膜系结构 $N_{Ag}=0.065-i_4$, $n_H=2.3$, $n_L=1.38$, $n_G=1.52$	(3) 反射率 R_P	R_S
1	$A\mid 0.67HL(HL)^2Ag\mid G \quad \lambda_0=865nm$	0.94	1.00
2	$A\mid 0.8HL(HL)^3Ag\mid G \quad \lambda_0=865nm$	0.96	0.99
3	$A\mid 0.87L(HL)^3Ag\mid G \quad \lambda_0=865nm$	0.95	0.99
4	$A\mid 0.21HL(HL)^4Ag\mid G \quad \lambda_0=865nm$	0.97	0.99
5	$A\mid 0.94HL(HL)^4Ag\mid G \quad \lambda_0=430nm$	0.97	0.97

Key: (1) Serial No. (2) Film System Structure (3) Reflection Efficiency

As far as this type of design method is concerned, although it is simple, the obtained film systems, however, with the only exception of the outermost layers, are non 1/4 wave length layers, and film thickness control is not very difficult. What is regrettable is that, as shown in Fig.2, under general circumstances, phase shift differences are relatively sensitive in following changes in film thicknesses. As a result, actual preparation and manufacture is difficult. Fig.3 is the status of phase shifts following along with changes in the outermost layer film thicknesses associated with film systems 2 and 3 in Table 1. These two designs still have rather tolerant thickness deviations. Besides this, this type of design method still carries with it a certain blindness. In conjunction with this, not all initial designs are capable of arriving at expected solutions.

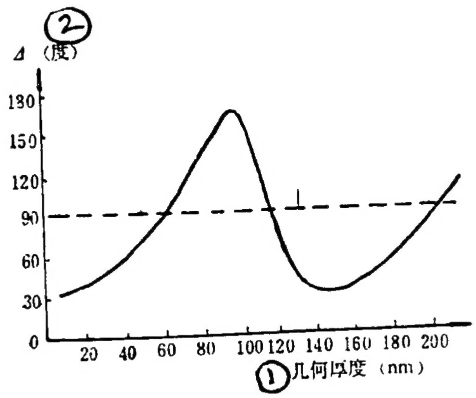
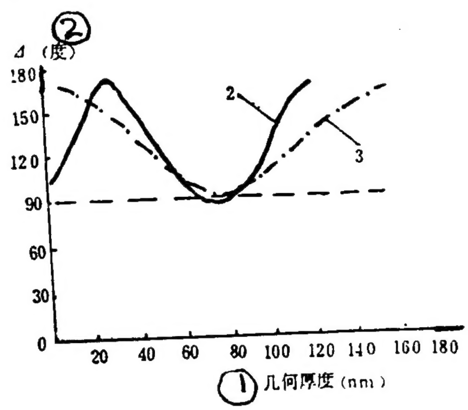


Fig.2 Changes in Phase Differences Following Along with Outermost Layer Thicknesses Associated with Film System 1 in Table 1

Key:(1) Geometrical Thickness (2) Degrees

Fig.3 Changes in Phase Differences Following Along with Outermost Layer Thicknesses Associated with Film Systems 2 and 3 in Table 1

Key: (1) Geometrical Thickness (2) Degrees



In order to obtain more numerous design parameters and better characteristics, we opted for the use of statistical experimental methods [5] on entire thin film systems to carry out optimization design. This type of method not only calculates velocities quickly. With TQ-16 devices, a complete design generally only requires 2-3 minutes, and that is it. Moreover, normally, in all cases, it is possible to solve for rational solutions. All film system reflection efficiencies obtained are high. Moreover, R_p and R_s are unusually close. Changes of phase difference along with wave length are relatively slow, and they are very close to 90°. Table 2 is a number of cases in which the methods in question were used for corrections.

Statistical test methods to design programs are explained simply as follows:

Evaluation functions F_j are composed of three parts, that is

$$F_i = W_s \sum_{j=1}^{m} (R_j^s - IR_j^s)^2 + W_p \sum_{j=1}^{m} (R_j^p - IR_j^p)^2 + W_F \sum_{j=1}^{m} (\Delta_j - I\Delta_j)^2$$

In the equation, $IR^s{}_j$, $IR^p{}_j$, and $I\Delta_j$ are, respectively, expressions of expected s and P component reflection efficiencies and phase differences. W_s, W_p, and W_F are three weighing factors. Due to the fact that R_p and R_s take part in evaluations, all design R_p and R_s obtained are relatively close. Practical realizations clearly demonstrate that this type of design method is successful. Problems only exist in that there are still certain difficulties in actually preparing these film systems.

TABLE 2. 90° PHASE FILMS (λ = 632nm) ASSOCIATED WITH STATISTICAL TEST METHOD CORRECTIONS

(1) 序号	1		2		3		4	
	n	nd	n	nd	n	nd	n	nd
(2) 基底	1.52							
1	Ag							
2	1.376	270.1	1.423	246.9	1.452	124.5	1.354	164.9
3	1.937	240.0	2.075	257.3	2.242	115.6	2.048	144.0
4	1.452	154.4	1.618	258.0	1.480	126.6	1.407	148.3
5	1.931	181.5	1.426	234.8	2.188	125.7	2.284	117.2
6	1.0		1.983	206.0	1.414	139.1	1.370	153.2
7			1.0		2.229	136.0	2.110	116.0
8					1.0		1.425	143.2
9							1.964	139.6
10							1.0	
R_p	0.95		0.96		0.97		0.99	
R_s	0.95		0.97		0.98		1.00	
Δ	90.3		90.3		89.7		90.1	

(3) 注：表中光学厚度单位为 nm。

Key: (1) Serial No. (2) Base (3) Note: In the table, the optical thickness unit is the nm.

III. TESTS AND RESULTS

We carried out experiments on the film systems obtained from the two types of design methods.

As was described before, the characteristics associated with film systems 2 and 3 in are relatively insensitive to thicknesses of the outermost film layers. Also, considering the

relationship between the Δ shown in Fig.4 and wavelengths, obviously, selecting film system 2 is more reasonable. At present, the key which experimentation must resolve is simply the two questions of film thickness control and wave length positioning. As far as thin film thicknesses are concerned, option is made for indirect methods of control. The reason is that, with regard to MgF_2 film tightly adhering to Ag layers, consideration has not yet been given to reflection phase shifts on Ag/MgF_2 boundary surfaces. Because of this, use is made of the first control plate to plate on Ag. The Ag thickness is approximately 1000-1500 A. Following this, replacement is done on the control plates already plated with preplating layers to complete plating various 1/4 wave length layers (using secondary control). The final layer left over only requires making simple standard value estimates, and that is all. Due to the fact that the permissible thickness difference associated with the final film layer is relatively broad, plating control precision, therefore, is not very strict.

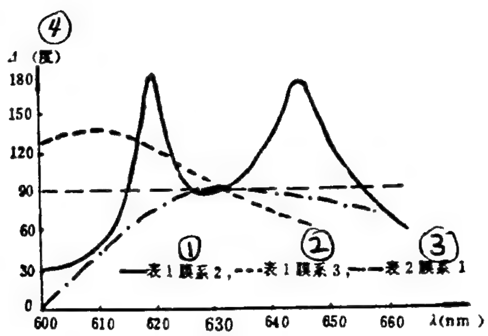


Fig.4 Changes in Phase Difference Δ Following Along with Wave Lengths and Corresponding to Film Systems 2 and 3 as Well as Table 2 Film System 1

Key: (1) Film System 2 (2) Film System 3 (3) Table 2 Film System 1 (4) Degrees

Thin film wave plate wave length positioning precision requirements are relatively high. Otherwise, there would be clear deviations from 90°. As a result, it is necessary to accurately adjust control wave lengths. In order to overcome blindness, it is possible to use Fig.4 to act as a guide. Once actual measurements have been carried out on samples, it is subsequently possible to judge in which direction to adjust control wave lengths.

/95

Tests were also carried out on Table 2's automatically designed film system 1. In actual preparation, the key problems which require solution are selecting appropriate thin film materials and film layer thickness control.

Using ZrO_2 to act as a material with refractive index 1.93, due to the fact that the actual refractive index is on the low side and does not reach design requirements, option is, therefore, made for the use of mixed materials ($ZnS+MgF_2$). In conjunction with this, calculations are made of the percentage weights of the two types of materials in accordance with the formula below:

$$n^2 = \frac{a_H n_H^2 c_H/\rho_H + a_L n_L^2 c_L/\rho_L}{a_H c_H/\rho_H + a_L c_L/\rho_L}$$

In the equation, $a_{H,L} = \frac{1}{n_{H,L}^2 + 2}$. ρ_H and ρ_L are the densities of the two types of materials. Moreover, c_H and c_L are their weight percentage concentrations. On the basis of the required refractive index of 1.93, calculations give $c_H = 0.743$ and $c_L = 0.257$. Besides this, the two types of materials are SiO_2 and MgF_2.

The remaining problem is film thickness control. For the sake of convenience, the film systems in question opt for the use of direct control. Beforehand, use is made of computers to calculate the transmission rates of various film layers after

plating is complete. Following this, the wave length (for example, 690nm) with relatively large transmission rate change amplitudes is selected to act as control wave length. Various film layer transmission rate changes are set out in Table 3. The control instrument is the MK-1 thickness control device. In order to make back surface media film control not cause difficulties, Ag layer thicknesses are selected as approximately 600 A. At this time, transmission rates on control wave lengths are approximately 0.62%.

TABLE 3 TRANSMISSION RATE CHANGES AND STANDARD VALUES ASSOCIATED WITH TABLE 2 FILM SYSTEM 1

(1) 膜层	Ag	MgF_2	$(ZnS+MgF_2)$	SiO_2	$(ZnS+MgF_2)$
(2) $\lambda_0=690nm$计算的$T\%$	0.62	0.72	2.11	1.04	3.69
(3) 预期的透射率变化	T ↓ 0.62	0.62 ↑ T_{max} ↓ 0.72	0.72 ↓ T_{min} ↑ 2.11	2.11 ↓ 1.04	1.04 ↓ T_{min} ↑ 3.69(T_{max})
(4) 实际格值变化	100—6.2 (×100挡换×10挡)	56—92—65 (用10进镀模拟)	7.2—3.5—20.5 (×10挡)	21—10 (×10挡)	10—8.8—37 (×10挡)
	(5)	(6)	(7)	(7)	(7)

Key: (1) Film Layer (2) T% Calculated with λ=690nm (3) Expected Transmission Rate Changes (4) Actual Standard Value Change (5) x100 setting changed to x10 setting (6) (Use 10 to enter plating simulation) (7) x10 setting

Measurements were carried out on a TP-77 elliptic polarization instrument. The light source is a He-Ne laser. Incident angle adjustment is at operating angle 45°. A readings stand for $tg\psi = r_p/r_s$. P readings stand for $\Delta = \delta_p - \delta_s$. Relative amplitude and relative phase differences measured in the actual preparation of the two film systems described above are

$tg\psi = 45.6^\circ$, $\Delta = 91.8^\circ$ (for film system 2)

$tg\psi = 45.9^\circ$, $\Delta = 90.4^\circ$ (for Table 2 film system 1)

One can see that the properties are good.

IV. CONCLUSIONS

As far as the two types of design methods introduced in this article are concerned, with regard to thin film wave plate design, they are effective. The first type of design method permits one to obtain aligned film systems almost the thickness of 1/4 wave length. As a result, film thickness control is very convenient. With regard to the second type of automatic design method--although it obtains relatively complicated film systems--it is easy, however, to get good film system characteristics.

In order to get highly reflective 90° phase films, metal films are necessary. For example, in the case of $ZnS-MgF_2$ full medium films, one opts for the use of the first type of design method. Although it is possible to satisfy amplitude ratio conditions--that being the case--the supplied phase differences, at most, are only 22.5°. Using the second type of automatic design method, it is still possible to reach 90° phase conditions. However, it is difficult to satisfy amplitude ratios. Metallic film thicknesses are generally around 300 A. Later, following increases in metallic film thicknesses, phase differences are basically maintained invariable. Only reflection rates continue to go up.

/96

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